



High Power Multimode Fiber Master Oscillator Power Amplifier (MOPA) with Stimulated Brillouin Scattering (SBS) Beam Cleanup and Phase Conjugation

by John E. McElhenny, Jeffrey O. White, and Steven D. Rogers

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14. ABSTRACT This is a study, at the 10^2 W power level, of the feasibility of using stimulated Brillouin scattering (SBS) beam cleanup and wavefront reversal to obtain 10^5 W of single-mode output from a multi-mode fiber amplifier. These techniques allow power scaling by circumventing the problem of maintaining single-mode operation in a fiber with a large core. We have achieved 51-W peak power (34 W average) out of the beam cleanup fiber master oscillator power amplifier (MOPA) system. We also demonstrated the use of a volume Bragg grating to outcouple the Stokes beam in such a system.					
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Contents

List of Figures	iv
List of Tables	iv
1. Introduction	1
2. Fiber Amplifier Simulations	2
3. Multimode Fiber Amplifier Experimental Results	3
4. Stimulated Brillouin Scattering Beam Cleanup & Wavefront Reversal	5
5. Beam Cleanup Fiber MOPA System	7
6. Outcoupling with a Volume Bragg Grating	8
7. Conclusions	10
8. References	11
List of Symbols, Abbreviations, and Acronyms	13
Distribution List	14

List of Figures

Figure 1. Fiber master oscillator power amplifier (MOPA) setups that use SBS (a) beam cleanup and (b) wavefront reversal to achieve a single mode output from a multimode fiber. The single mode Stokes light is outcoupled with a volume Bragg grating (VBG). The multimode fiber is a ytterbium (Yb)-doped large mode area (LMA) fiber.	1
Figure 2. Liekki Application Designer simulations of the (a) single pass and (b) double pass geometry assuming 100% coupling efficiency, 80% SBS reflectance, 100% outcoupling, 7 W of seed, and 141 and 120 W of pump, respectively.	2
Figure 3. The preliminary beam cleanup fiber MOPA setup using a Faraday isolator to outcouple the Stokes wave.	3
Figure 4. The amplified power transmitted through a 5.2-m Liekki1200Yb30-250 DC-PM along the slow axis (blue) and at 45° from the slow axis (red).	4
Figure 5. The SBS reflectance (green) and transmittance (blue) through the 2.7-km GI 50/125 fiber.	5
Figure 6. (a) The output of the fiber amplifier without the 976-nm pump, (b) the Fresnel reflection from the GI fiber and (c) the backscattered Stokes wave superimposed over the Fresnel reflection.	6
Figure 7. (a) The output of the fiber amplifier pumped by the 976-nm light, (b) the Fresnel reflection from the GI fiber, and (c) the backscattered Stokes wave superimposed over the Fresnel reflection.	6
Figure 8. The 1064-nm amplified power transmitted through the fiber amplified (red squares), transmitted through the Faraday isolator (orange circles), transmitted through the GI fiber (blue up triangles), and backscattered from the GI fiber (purple diamonds). Also plotted is the 976-nm pump power transmitted through the fiber amplifier (green down triangles).	8
Figure 9. Calculated (line) and measured (circles) reflection of a 12-mm-thick reflection volume Bragg grating.	9
Figure 10. The VBG transmittance at λ_L (blue), VBG reflectance at λ_S (red), and SBS reflectance (black).	10

List of Tables

Table 1. Parameters of various fibers considered for use in wavefront reversal.	7
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1. Introduction

Fiber wavefront reversal and beam cleanup could be key techniques for scaling fiber and solid-state lasers to the 100-kW power level while maintaining high beam quality. The current state-of-the-art for single-mode output is ~ 10 kW from a 25–30 μm diameter core (1). The techniques we are developing could lead to an order of magnitude increase in mode area and an order of magnitude increase in power.

Stimulated Brillouin scattering (SBS) currently limits the power scaling of narrow-bandwidth fiber amplifiers. Wider bandwidth, shorter fibers, or larger mode areas are needed to avoid SBS in the amplifier. Increasing the bandwidth of the seed laser has drawbacks if multiple lasers are to be coherently combined at a later stage. Efficient absorption of the pump calls for longer fibers. The difficulty with substantially increasing the mode area is that the amplifier becomes highly multimode, reducing the beam quality.

Our goal is to show how SBS in an auxiliary fiber can be used to obtain fundamental mode output from a highly-multimode fiber amplifier. One approach uses a single-pass amplifier (figure 1a), followed by beam cleanup in a separate fiber (2, 3). A second approach uses a double-pass amplifier (figure 1b) with an intermediate step of wavefront reversal. Our goal was to test both techniques on the basis of a 100-W fiber laser demonstration.

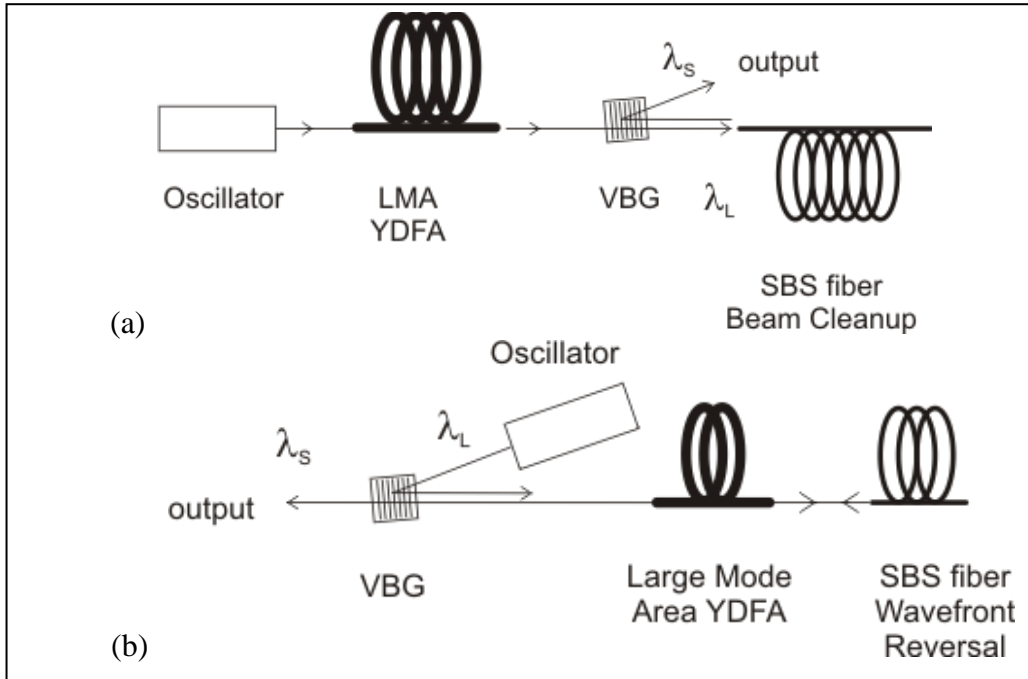


Figure 1. Fiber master oscillator power amplifier (MOPA) setups that use SBS (a) beam cleanup and (b) wavefront reversal to achieve a single mode output from a multimode fiber. The single mode Stokes light is outcoupled with a volume Bragg grating (VBG). The multimode fiber is an ytterbium (Yb)-doped large mode area (LMA) fiber.

2. Fiber Amplifier Simulations

To determine the necessary pump power and the optimal length of the fiber amplifier, we used Liekki Application Designer 4.0. One limitation of the software is that SBS is not taken into account. In both the *single-pass beam cleanup* (figure 1a) and *double-pass wavefront reversal* (figure 1b) geometries, 7 W of seed, 100% efficiency for coupling the pump into the cladding, 80% SBS reflectivity, and 100% outcoupling efficiency were assumed. The fibers under test are the Liekki Yb1200 series of fibers, which are double clad (DC) and polarization maintaining (PM). The core diameters are 20, 25, and 30 μm . All fibers have an inner cladding diameter of 250 μm . Figure 2 shows the Liekki Application Designer simulations.

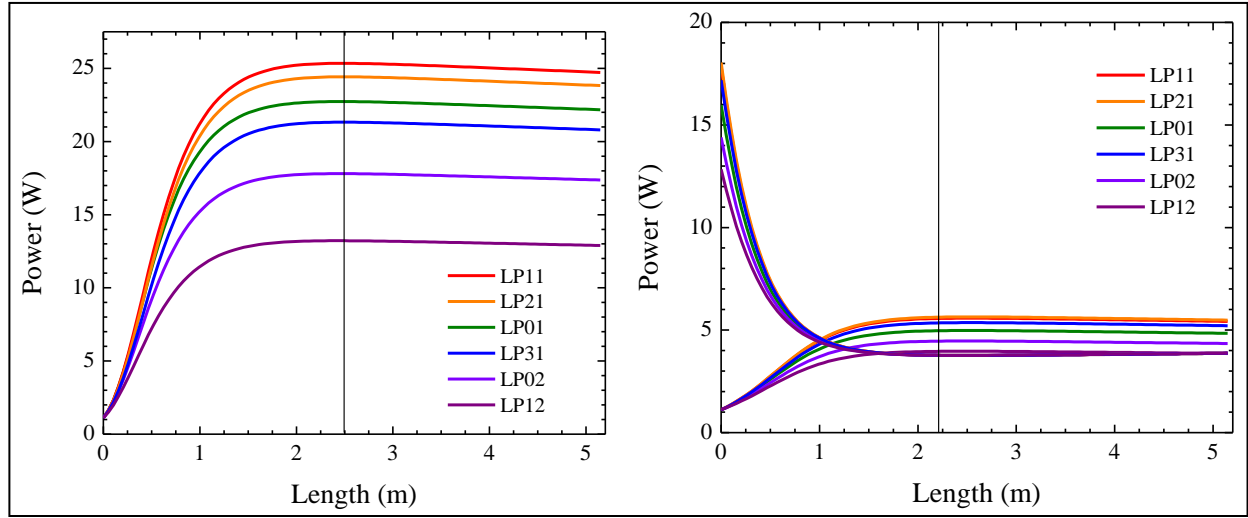


Figure 2. Liekki Application Designer simulations of the (a) single pass and (b) double pass geometry assuming 100% coupling efficiency, 80% SBS reflectance, 100% outcoupling, 7 W of seed, and 141 and 120 W of pump, respectively.

In the *single pass* geometry, 141 W of pump power is needed to achieve 125 W of amplified power through the fiber amplifier and thus 100 W out of the system. The ideal fiber amplifier length is 2.5 m. In the *double pass* geometry, only 120 W of pump power should be necessary. The ideal length of the fiber amplifier in this geometry is ~ 2.2 m. After the first pass, the seed light is amplified to 29 W, considerably less than with the single pass geometry. This makes finding the ideal fiber for wavefront reversal more difficult, as discussed in section 3. Because the coupling and outcoupling efficiency are likely to be less than 100%, these estimates of required pump power are somewhat optimistic.

3. Multimode Fiber Amplifier Experimental Results

For the rest of this report, we use the 5.2-m Liekki Yb1200-30/250 DC-PM as the fiber amplifier. Using a long wavepass (LWP) dichroic mirror, we couple up to 200 W of 976 nm pump into the inner cladding and 7 W of 1064-nm seed light into the core. The unabsorbed pump light is separated from the amplified seed using another LWP dichroic. In the *beam cleanup* geometry (see figure 1a), the amplified light passes through the isolator and into the fiber designed for SBS beam cleanup, generally a long, graded-index (GI) fiber. Here, we use a 2.7-km GI 50/125 fiber (4). The backscattered Stokes wave is outcoupled using a Faraday isolator. Figure 3 shows the preliminary beam cleanup fiber MOPA setup using a Faraday isolator.

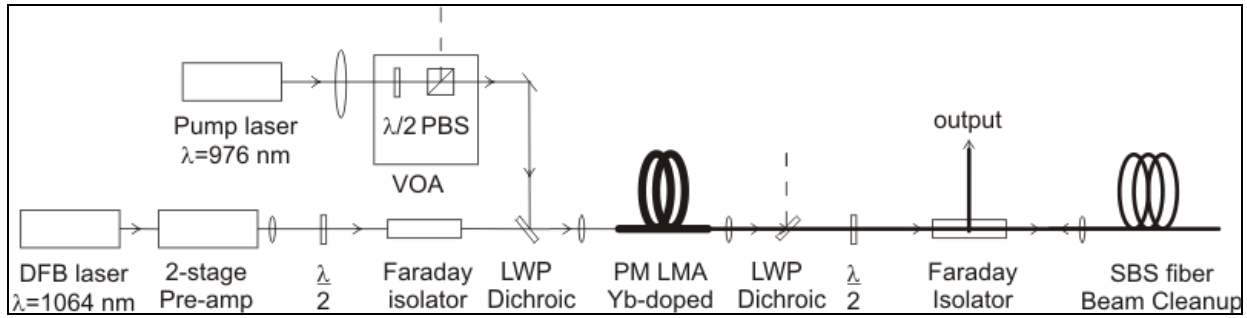


Figure 3. The preliminary beam cleanup fiber MOPA setup using a Faraday isolator to outcouple the Stokes wave.

Using this system, we obtained 65 W of peak power for a 1064-nm seed of 7-W polarized power along the slow axis of the fiber and a 976-nm pump of 200-W peak power at 10% duty cycle (6 ms, 16 Hz) (figure 4). The lower than expected output power is due to SBS, the non-optimal length of the fiber, and the less than 100% coupling of the pump light into the inner cladding.

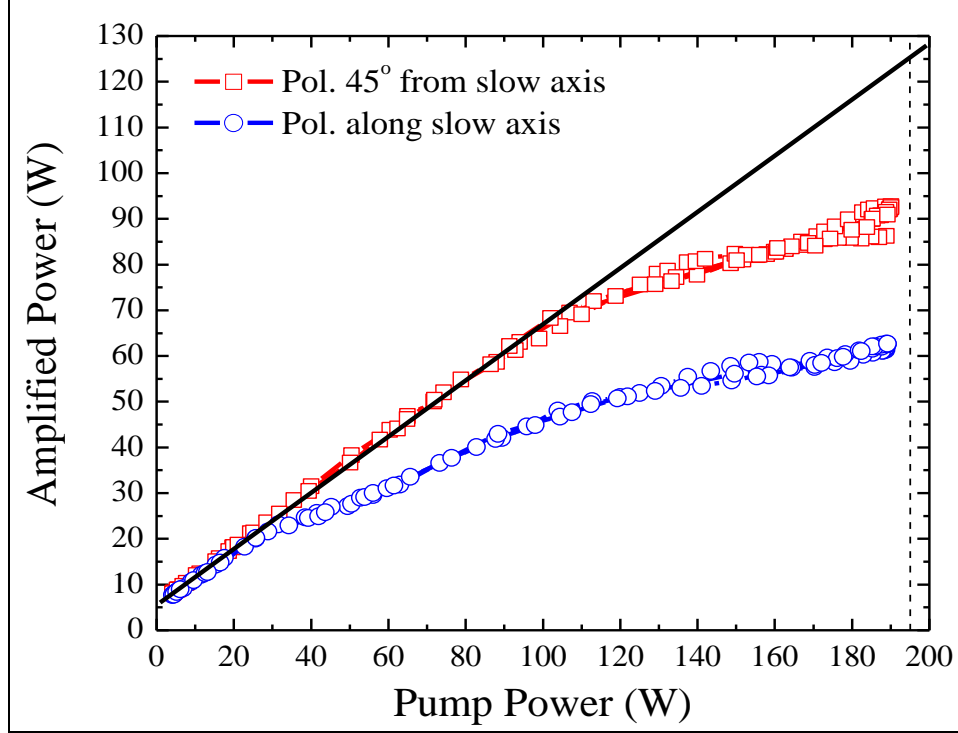


Figure 4. The amplified power transmitted through a 5.2-m Liekki1200Yb30-250 DC-PM along the slow axis (blue) and at 45° from the slow axis (red).

For light polarized along the slow axis (blue circles), SBS is observed above a pump power of ~30 W and greatly limits the transmission. As mentioned previously, the fiber amplifier is more than twice the optimal length of 2.5 m. Cutting the fiber in half should double the threshold. Likewise, the input light being polarized at 45° from the slow axis (red squares) also doubles the threshold. Upon cutting the fiber from 5.2 to 2.9 m, we obtained a 105–110 W peak power out of the fiber amplifier. Though we haven't yet tried it, counter-propagating the pump and seed might further increase the SBS threshold enough to allow amplification to reach the full 125 W.

Another improvement to make would be to increase the coupling efficiency of the pump light into the inner cladding, which is currently only about 70%. This indicates that although 200 W of pump light is incident upon the fiber, only ~140 W is coupled into the inner cladding.

The black line in figure 4 is the projected amplified power assuming no SBS, a scenario we should have when we counter-propagate the pump and seed. At 200 W of pump (140 W actually coupled into the inner cladding), the amplified power should be between 125 and 130 W, matching the simulation results.

Improving the coupling, further reducing the fiber length and counter-propagating the pump and seed would allow one to achieve even higher amplified powers.

4. Stimulated Brillouin Scattering Beam Cleanup & Wavefront Reversal

In general, it is seen that SBS produces beam cleanup in long GI fibers and wavefront reversal in short step-index (SI) fibers (2, 3). This is explained, as least in part, by the fact that in SI fibers, all transverse modes of the Stokes wave should experience the same gain, while in GI fibers, the gain is higher for the lower order modes.

For the *single-pass beam cleanup* approach, we characterized a 2.7-km 50/125 GI fiber (4) using a single-mode 1064-nm seed. The fiber has an SBS threshold of 200 mW and a reflectivity up to 86% (figure 5). Sending in a multimode beam, generated through the fiber amplifier both without (figure 6) and with (figure 7) the 976-nm pump on, we have found that the GI fiber produces a single-mode beam.

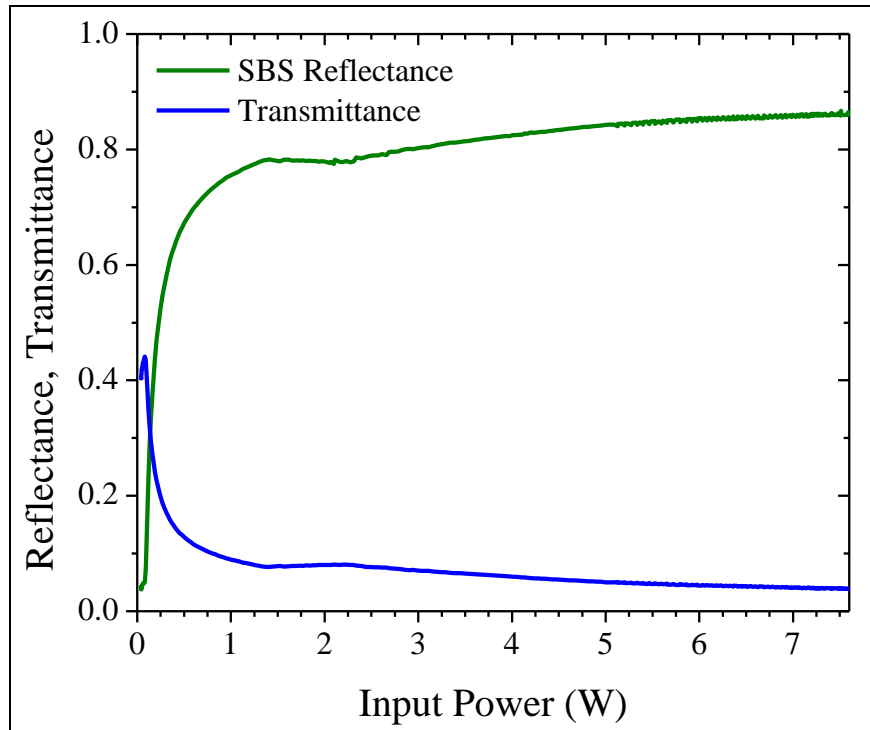


Figure 5. The SBS reflectance (green) and transmittance (blue) through the 2.7-km GI 50/125 fiber.

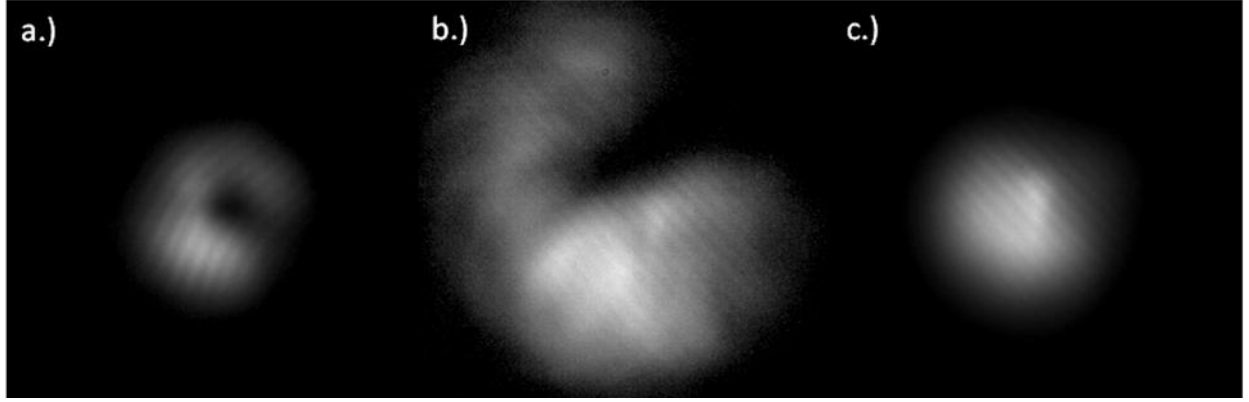


Figure 6. (a) The output of the fiber amplifier without the 976-nm pump, (b) the Fresnel reflection from the GI fiber and (c) the backscattered Stokes wave superimposed over the Fresnel reflection.

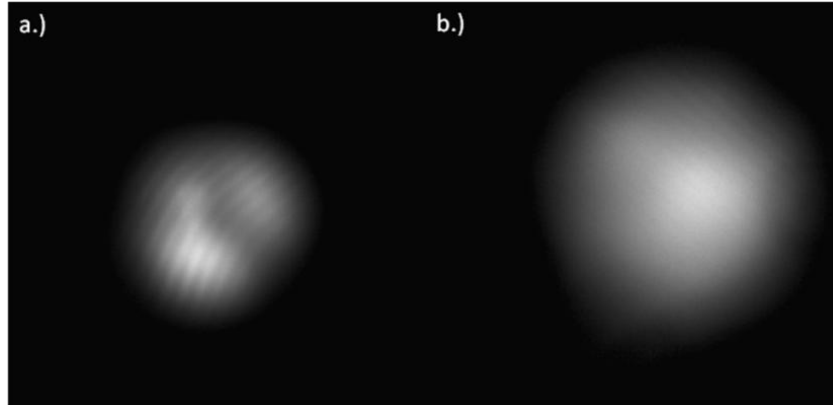


Figure 7. (a) The output of the fiber amplifier pumped by the 976-nm light, (b) the backscattered Stokes wave superimposed on the Fresnel reflection from the GI fiber.

For the *double-pass wavefront reversal* approach, a short standard SI fiber has a threshold that is too high to produce high-reflectivity SBS after the first pass, given the available power. We analyzed a number of alternatives to short standard SI fibers (table 1). The core diameter, NA, V-number, and Brillouin gain are intrinsic properties of the fiber. The length is set to give a fidelity of 0.8 from the equation $F = A + B \exp[-C(L\Omega_B NA^2)^2]$ developed by Massey (5). The SBS threshold is determined from $P_{th} = 21 A_{eff} / (g_B L_{eff})$.

Table 1. Parameters of various fibers considered for use in wavefront reversal.

	CorActive		Liekki (passive DC PM LMA)		
Fiber	MM-20/125	Ge740	20/250	25/250	30/250
d_{core} (μm)	20	40	20	25	30
NA	0.13	0.06	0.07	0.07	0.07
V	7.7	7.1	4.1	5.2	6.2
g_B (10^{-11} m/W)	1.8	4.3	2	2	2
L (m)	12	57	42	42	42
P_{th} (W)	30.9	13.1	9.6	15.0	21.6

Custom-drawing a 20- μm -core multimode fiber (MM-20/125) or a germanium (Ge)-doped 40- μm fiber (Ge740) would reduce the threshold, but not down to the level of 2–3 W. Filling the core of a hollow-core photonic bandgap fiber with methane would have a low enough threshold for our system; however, the cost for a length of ~ 100 m is prohibitive, and the standard hollow-core fiber supports only a single mode at 1064 nm.

Brignon et al. (6) have shown that the wavefront reversal fidelity of the SI fiber is close to 100% for short fibers, but drops to zero at lengths above ~ 1 m, while in GI fibers, it is initially lower (~ 70 – 80%) but persists at that level until ~ 100 m. A 100-m GI fiber with a small core size would be an attractive option, but custom fiber draws are expensive. Finally, a SI fiber that exactly matches the parameters of the fiber amplifier, i.e., an undoped Liekki fiber, provides a threshold that is low, but not low enough (table 1).

5. Beam Cleanup Fiber MOPA System

Coupling up to 200 W of a 976-nm pump at a 70% duty cycle and 7 W of a 1064-nm seed light into the inner cladding and core, respectively, of a 30- μm -core, 250- μm inner cladding polarization-maintaining 2.8-m Yb-doped Liekki fiber, we achieved a 109-W peak power (73-W average power) of amplified seed light through the fiber (figure 8). With a 76-W peak power (51-W average power) through the Faraday isolator and coupled into a 2.7-km GI 50/125 fiber, the 51 W-peak power (34-W average power) is then coupled out of the system using the Faraday isolator. Replacing with the VBG should improve both the outcoupling and the power scalability of the system. Further decreasing the amplifier length, achieving better pump coupling, and counter-propagating the seed and pump will reduce the SBS in the fiber amplifier and allow us to obtain more power from the system.

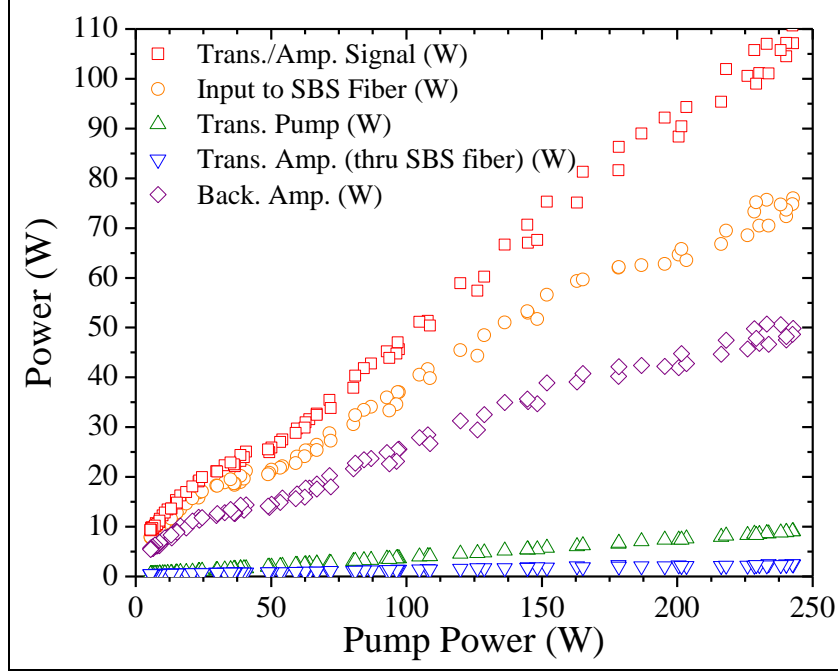


Figure 8. The 1064-nm amplified power transmitted through the fiber amplifier (red squares), transmitted through the Faraday isolator (orange circles), transmitted through the GI fiber (blue up triangles), and backscattered from the GI fiber (purple diamonds). Also plotted is the 976-nm pump power transmitted through the fiber amplifier (green down triangles).

6. Outcoupling with a Volume Bragg Grating

In the above experiments, outcoupling was done in the conventional way with a Faraday isolator, which works because the Stokes wave is counter-propagating to the laser. To circumvent the power scaling limitation imposed by the Faraday isolator, we investigated the use of a VBG. A VBG can separate the Stokes and laser waves based on the wavelength shift, just as in a conventional diffraction grating. Photo-thermo-refractive (PTR) glass can be made with a loss below 10^{-3} cm^{-1} , and a damage threshold above 10^4 W/cm^2 , therefore VBGs have the potential for scaling to higher powers, provided the area is large enough. A 12-mm-thick VBG with $8 \times 12 \text{ mm}^2$ faces was fabricated from PTR glass (7) and tested at power levels up to 6 W (8).

Since the initial study, our collaborators (7) have obtained higher-resolution transmission spectra that agree well with the coupled-wave simulation (figure 9). The full width at half maximum (FWHM) of the simulation is 0.063 nm; the experimental data has a FWHM of 0.057 nm. The asymmetry in the side lobes of the measured curve could be due to a z-dependent background index change or grating period distortion (9, 10). Based on the low power measurements in figure 9, the figure of merit appropriate for the geometry of figure 1b, $R_L T_S$, could be as high as

0.96. The figure of merit appropriate for figure 1a, $T_L R_S$, would be slightly less, 0.94, but easier to obtain experimentally because the short wavelength sidelobes are much smaller (figure 9).

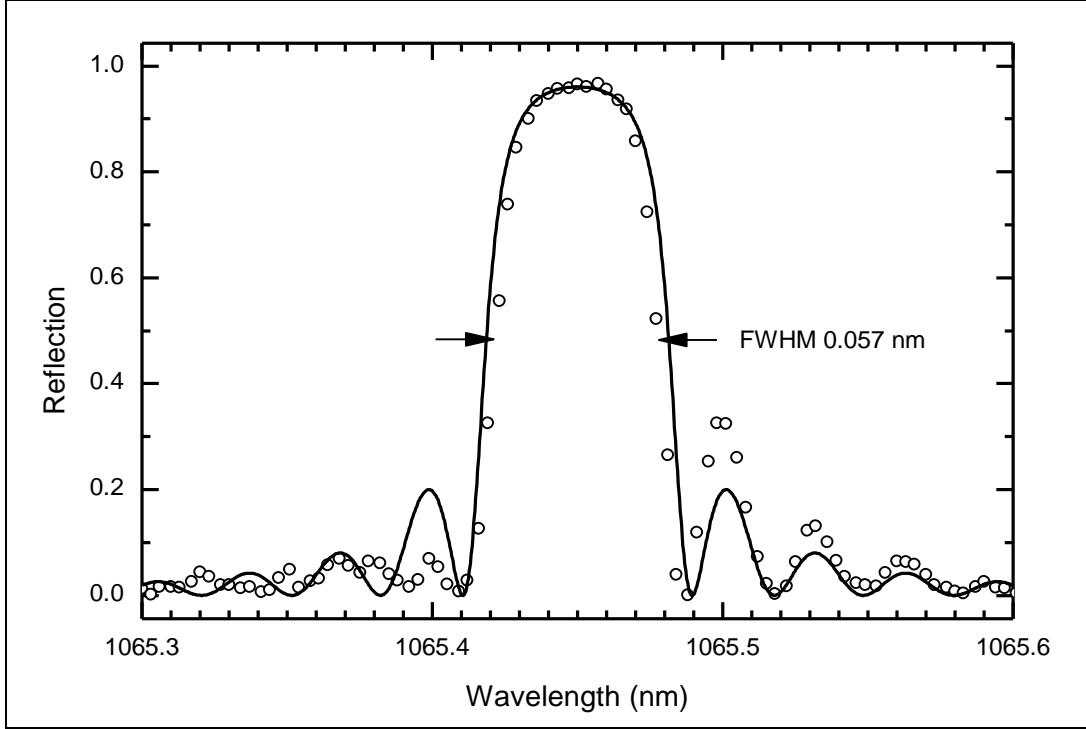


Figure 9. Calculated (line) and measured (circles) reflection of a 12-mm-thick reflection volume Bragg grating (7).

Since the initial study, we characterized the VBG at higher power levels, in both geometries of figure 1. The oscillator shown in figure 1 was a VBG-stabilized diode laser (11) amplified to 30 W with a single-mode, polarization-maintaining Yb-doped fiber amplifier (12). The delivery fiber has a numerical aperture of 0.06; the output is collimated to a 3.0 mm diameter with a 25-mm focal length doublet (13). A half-wave plate and Faraday isolator serve as a variable optical attenuator. The separate amplifiers shown in figure 1 were not used. To obtain the backward Stokes beam, light at λ_L is focused with a 30-mm focal length doublet into a 2.7-km graded-index fiber with a 50- μm core and numerical aperture of 0.2 (14). Beam samplers at a small angle of incidence monitor incident, reflected, and transmitted powers. The VBG is aligned to maximize the Bragg reflection at an angle of 10° .

In the geometry of figure 1b, the VBG transmittance at λ_L is 0.95 and the reflectance at λ_S is 0.94 at an input power of 27 W (figure 10). The figure of merit of the VBG is $T_L R_S = 0.89$. The light reflected from the fiber shows the characteristic threshold behavior of SBS, at 0.2 W incident upon the fiber. The highest SBS reflectance we observe is 0.81.

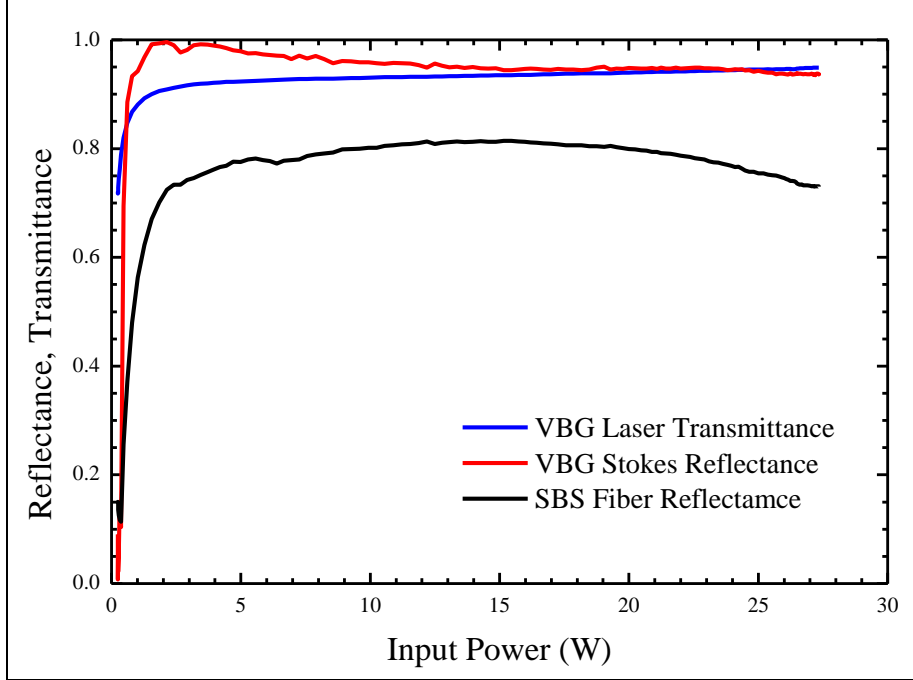


Figure 10. The VBG transmittance at λ_L (blue), VBG reflectance at λ_S (red), and SBS reflectance (black).

7. Conclusions

Fiber wavefront reversal and beam cleanup could be key techniques for scaling fiber lasers to the 100-kW power level. Both techniques involve suppressing SBS in the amplifier and exploiting SBS in an auxiliary fiber. SBS in the amplifier is suppressed by using a large core, multimode fiber. SBS in the auxiliary fiber is used to either (1) create a wavefront reversed replica of the multimode beam, prior to a second pass through the amplifier, or (2) convert the multimode beam to a fundamental mode in a single pass configuration.

Using the beam cleanup MOPA setup, we have achieved a 51-W peak power (34-W average power) of nearly fundamental mode output from a multimode amplifier. These results should be improved with better pump coupling, a shorter fiber amplifier, and a counter-propagating pump.

In the wavefront reversal MOPA setup, for the 10–100 W power levels in our demonstration project, there are a number of fibers that could potentially meet the required specifications, but none are commercially available. At a power level of 10^3 W and above, the commercially available fibers in table 1 would make the system experimentally feasible.

We have also addressed the power scaling limitations of a Faraday isolator by introducing an outcoupler based on a state-of-the-art VBG with a figure of merit of 0.89. We have tested it at intensities up to ~ 400 W/cm².

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List of Symbols, Abbreviations, and Acronyms

DC	double clad
FWHM	full width at half maximum
Ge	germanium
GI	graded-index
LMA	large mode area
LWP	long wavepass
MOPA	master oscillator power amplifier
PM	polarization maintaining
PTR	photo-thermo-refractive
SBS	Stimulated Brillouin scattering
SI	step-index
VBG	volume Bragg grating
Yb	ytterbium

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